

Common origin of the high energy astronomical gamma rays, neutrinos and cosmic ray positrons?

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ABSTRACT

We show that the observed fluxes, spectra and sky distributions of the high energy astronomical neutrinos, gamma rays and cosmic ray positrons satisfy the simple relations expected from their common production in hadronic collisions in/near source of high energy cosmic rays with diffuse matter.

Subject headings: (ISM): gamma rays, neutrinos, dark matter

1. Introduction

Nearly half a century ago it has already been realized that the decay of mesons produced in the interactions of high energy cosmic rays (CRs) with matter and radiation in/near the cosmic ray sources, in the interstellar medium (ISM), and in the intergalactic medium (IGM), can produce detectable fluxes of high energy gamma rays (γ 's), neutrinos (ν 's) and positrons (e^+ 's), which carry unique information on the ultra relativistic universe (e.g., Zatsepin & Kuzmin 1966; Berezhinsky & Smirnov 1975; Margolis et al. 1978; Eichler 1978; Eichler & Schramm 1978; Stecker 1979). In particular, interaction of cosmic rays with diffuse matter and/or radiation in/near the cosmic ray sources, in the ISM of Galaxies and the IGM has long been recognized as possible point and diffuse sources of very high energy Galactic and extragalactic γ -rays and neutrinos (see, e.g., Dar 1983,1985,1991; Halzen et al. 1990; Berezhinsky 1991; Stecker et al. 1991; Mannheim 1993; Berezhinsky et al. 1993,1994; Domokos et al. 1993; Dar & Shaviv 1996; Halzen 1996; Dar & Laor 1997).

The successful detection of neutrinos from supernova 1987A with the deep underground Kamiokande and IMB water Cherenkov telescopes, of Galactic and extragalactic point sources of very high energy γ -rays with ground based atmospheric and water Cherenkov telescopes (see, e.g., Weekes et al. 1989; Punch et al. 1992), and of point sources and diffuse Galactic and extragalactic backgrounds of high energy γ -rays with the Compton

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Gamma Ray Observatory (Hunter et al. 1997; Sreekumar et al. 1998), have led to the development of new generations of much larger and more sensitive telescopes of high energy γ -rays, neutrinos and cosmic rays, which have already made several breakthrough observations. Such breakthroughs include the discovery of a diffuse high energy neutrino background radiation (NBR) with the megaton IceCube detector under the south pole (Aartsen et al. 2013,2014,2015), the accurate measurement of the diffuse high energy gamma-ray background radiation (GBR) with the Large Area Telescope (LAT) aboard the Fermi satellite (Ackermann et al. 2012,2015), and the precise measurements of the high energy local background of cosmic ray positrons with the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) satellite (Adriani et al. 2013) and the Alpha Magnetic Spectrometer (AMS) aboard the International Space Station (Aguilar et al. 2014).

Possible sources and the detailed properties of the observed astronomical neutrinos, γ -rays and positrons were discussed in the discovery papers and in a large number of publications, which followed the observations (for a recent review see, e.g., Anchordoqui et al. 2014a). But, most of the published theoretical estimates of the fluxes of the high energy neutrinos, γ -rays and positrons from point sources and diffuse sources, both before and after these recent breakthrough observations, were fraught with uncertainties concerning the production mechanisms of the high energy neutrinos, γ -rays and positrons and the properties of their sources, which have left the origin and observed properties of these radiations essentially unsolved puzzles.

In view of such difficulties, several authors have tried alternative approaches towards resolving these puzzles, such as deriving upper bounds on the observed fluxes of the high energy astronomical neutrinos, gamma-rays and positrons, or general relations between them, which may indicate their origin. E.g., a highly cited "model-independent upper bound" on the energy flux of extragalactic NBR above 100 TeV was derived by Waxman & Bahcall (1999). It was based on the assumption that the NBR is produced by the decay of π^+ 's produced by the extragalactic cosmic ray protons in proton-photon collisions in the extragalactic CR sources. However, as shown in Appendix A1, the "model independent upper bound" of Waxman & Bahcall (1999), actually, is a model dependent estimate based on an incorrect extrapolation of the observed flux of extragalactic CRs to lower energies and on incomplete consequences of their arbitrary choices. When properly corrected, this "upper bound" increases by nearly *two orders of magnitude!* (see Appendix A1) and becomes useless.

Other authors have tried to relate the NBR discovered with IceCube and the high energy gamma-ray background radiation (GBR) measured with Fermi-LAT, assuming that both were produced in hadronic interactions of high energy cosmic rays (e.g., Murase et al. 2013; Anchordoqui et al. 2014a and references therein). However, most of these attempts were

based on the uncertain assumptions that the NBR is mostly extragalactic in origin and that the very high energy γ -rays from blazars and other extragalactic point sources are leptonic in origin. Consequently, the NBR was related only to the diffuse intergalactic gamma-ray background (IGRB), ignoring the possibility of a much larger Galactic contribution and an extragalactic contribution (e.g. from blazars):

Multiwavelength observations of blazars have shown that their spectral energy density usually exhibits two bumps, one at low energy (infrared to X-rays) and one at high energy (see, e.g., Abdo et al. 2010 and references therein). The origin of the high energy bump near TeV is still under debate (see, e.g., Cerruti et al. 2015 and references therein). Moreover, current Cherenkov telescopes have identified a population of ultra-high-frequency peaked BL Lac objects (UHLs), which exhibit exceptionally hard TeV spectra. This hard emission, as well as the high energy emission in gamma-ray bursts (GRBs) challenge the synchrotron-self-Compton (SSC) model (e.g., Konigl 1981) of very high energy γ -ray emission from blazar jets (Maraschi et al. 1992; Bloom & Marscher 1996) and from GRB jets (e.g., Dado & Dar 2005,2009). In particular, the standard one zone synchrotron-self-Compton (SSC) interpretation of the double peaked blazar spectra (see e.g., Abdo et al. 2010 and references therein) implies that the SSC peak frequency is inversely proportional to the synchrotron peak frequency because of the Klein Nishina suppression of the high energy inverse Compton scattering cross section. Such a correlation does not seem to be present in the observational data. In fact, the Klein-Nishina suppression of inverse Compton scattering of background photons by high energy electrons and the suppression of the population of high energy electrons by synchrotron radiation and inverse Compton scattering from background photons suggest that $\pi^0 \rightarrow 2\gamma$ decay following inclusive production and decay of mesons in jets encounters with diffuse matter may become the dominant production mechanism of very high energy photons emitted by blazars (Dar & Shaviv 1996; Dar & Laor 1997) and GRBs (Dado & Dar 2005,2009).

If the main origin of the very high energy astronomical neutrinos and γ -rays and CR positrons observed near Earth is the decay of mesons produced in high energy CR collisions with diffuse matter in/near the CR sources, and/or in the ISM, and/or in the IGM, then under very general assumptions their fluxes, spectra and sky distributions are simply related. In this paper, we reconsider such relations (e.g., Dado & Dar 2014) and confront them with observations rather than prejudices. Indeed, we show that the high energy NBR observed with IceCube and the GBR observed with Fermi-LAT (and the high energy Cherenkov telescopes) satisfy the simple relations expected from hadronic production of mesons by high energy cosmic rays in collisions with diffuse matter in/near source (rather than with diffuse radiation - see Appendix A2). They imply a non isotropic NBR whose sky distribution is similar to that of the Fermi-LAT GBR. We also show that the flux of the high energy CR

positrons observed near Earth with PAMELA and AMS02 is that expected from secondary production of mesons in the local ISM by the flux of cosmic ray nucleons (protons and nucleons bound in atomic nuclei) observed near Earth.

2. CR production of secondaries

Hadronic collisions of high energy nucleons of energy E_p with diffuse matter produce γ -rays, ν 's and e^\pm 's mainly through π and K decays. If the lab frame energy E of these secondary particles is expressed as $x E_p$, the distribution of x is independent of E_p to a good approximation (Feynman 1969). Consequently, a flux $\Phi_p \propto E_p^{-\beta}$ of CRs in a diffuse matter produces through hadronic collisions secondary γ -rays, ν 's, and e^\pm 's with a flux per unit volume (e.g., Dar 1983)

$$\Phi_i(E) \propto \sigma_{in}(E_p) n_s c \Phi_p(E_p) / \bar{x}_i \quad (1)$$

where $i = \gamma, \nu, \text{ or } e^\pm$, the mean value \bar{x}_i depends only on the distribution of x in the inclusive production $pp \rightarrow i X$ but not on E , $E_p = E/\bar{x}_i$ is the mean energy of cosmic ray protons that produce particles i with energy E , and $\sigma_{in} \approx 30 \times (E_p/\text{GeV})^{0.058}$ mb is the pp total inelastic cross section.

Eq. (1) implies that CR collisions with diffuse matter produce secondary fluxes of γ -rays, ν 's and e^\pm 's with the same power-law spectrum $\sim E^{-\beta+0.058}$ and different normalization. These fluxes are later modified by propagation effects: attenuation of high energy γ -rays mainly by Compton scattering from free electrons and by pair production on background photons, oscillations of neutrinos in space that spread the neutrino flux over the three neutrino flavors, diffusion propagation of high energy e^\pm 's in magnetic fields, and energy loss of e^\pm 's by synchrotron emission and inverse Compton scattering of background photons.

3. The GBR-NBR connection

We shall assume that the main kinds of sources of high energy cosmic rays (supernova explosions, merger of compact stars, and mass accretion onto compact stars, stellar mass black holes and massive black holes) are common to our Galaxy and external galaxies, that Fermi acceleration (Fermi 1949) and galactic confinement produce a power-law spectrum $\Phi_p \sim E^{-\beta}$ of galactic CRs, and that the main source of background γ -rays and neutrinos above TeV is hadronic collisions of these high energy CRs with diffuse matter inside or near the CR sources, in the ISM of their host galaxies, and in the IGM, which produce mesons (mostly pions and K mesons) that decay to high energy γ -rays, ν 's and e^\pm 's. The assumption

of hadronic rather than leptonic production is based on the facts that inverse Compton scattering of background photons by high energy electrons is suppressed by the Klein Nishina cross section and that the population of high energy electrons is suppressed by synchrotron radiation and inverse Compton scattering from background photons. (Photoproduction has an effective threshold too high to explain the high energy GBR observed below TeV). The hadronic production hypothesis, mostly overlooked, will be confronted here with observations rather than with prejudices.

Consider first hadronic production of high energy γ -rays and neutrinos by cosmic ray collisions with diffuse matter inside or near the CR sources.

The local flux of high energy cosmic ray nucleons (free protons and nucleons bound in atomic nuclei that hereafter will be denoted by p) between several GeV and the cosmic ray knee energy $E_{\text{knee}} \approx 1 \text{ PeV/nucleon}$ is well described by

$$\Phi_p(E) \approx C (E/\text{GeV})^{-\beta} \text{ fu} \quad (2)$$

where $C \approx 1.8$, $\beta \approx 2.70$ (e.g., Olive et al. 2014), and $\text{fu} = 1/(\text{GeV cm}^2 \text{ s sr})$ is the flux unit. Between the CR ‘knee’ and CR ankle at $E \sim 3 \text{ EeV}$, $C \approx 114$, and $\beta \approx 3.0$ (Apel et al. 2013). We will ignore the small differences between CR protons and nucleons bound in CR nuclei (A,Z) at the same energy per nucleon, because such nucleons contribute only a few percents to the total CR p flux and most of them are bound in light nuclei whose inelastic cross section per nucleon is $\sim \sigma_{\text{pA}}/A \approx \sigma_{\text{pp}}$, i.e., roughly the same as that of free protons.

CR protons escape the Galaxy by diffusion through its turbulent magnetic fields. For a Kolmogorov spectrum (Kolmogorov 1941) of random magnetic fields, their escape time satisfies $\tau_{\text{esc}}(E) \propto E^{-1/3}$. In a steady state, the supply rate of high energy CR protons by the Galactic CR sources (s) per unit volume is equal to their escape rate from the Galaxy. Hence, the source spectrum of CR protons satisfies $\Phi_s \propto \Phi_p/\tau_{\text{esc}} \propto E^{-\beta_s}$ where $\beta_s = \beta - 1/3$. Roughly, $\beta_s = \beta - 1/3 \approx 2.37$ for $E < E_{\text{knee}}(p)$, which is consistent with Fermi acceleration modified by escape by diffusion, and $\beta_s \approx 2.67$ for $E_{\text{knee}}(p) < E < E_{\text{ankle}}(p)$.

We shall assume that above 100 GeV the contribution of electron bremsstrahlung and inverse Compton scattering of background photons to the GBR, that decreases with increasing energy, becomes relatively small compared to the contribution from Galactic and extragalactic γ -ray production by $\pi^0 \rightarrow 2\gamma$ decays. Neutrinos are produced mainly by π and K decays.

As long as the neutrinos and gamma-rays are produced mainly through π decay by CRs with energy below the CR knee whose in/near source spectral index is $\beta_j \approx 2.7 - 1/3 - 0.06 \approx 2.31$, their fluxes satisfy

$$\Phi_\nu(E) \approx (m_{\pi^+}/2m_{\pi^0})^{1.31} \Phi_\gamma(E) \approx 0.39 \Phi_\gamma(E) \quad (3)$$

per ν flavor. At higher energies neutrinos are produced mainly through $\pi^\pm \rightarrow \mu^\pm \nu$ and $K^+ \rightarrow \mu^+ \nu_\mu$ decays followed by $\mu^\pm \rightarrow e^\pm 3\nu$ decay, and in $K^+ \rightarrow \pi^+ \pi^0$; $2\pi^+$, π^- ; $2\pi^0 \pi^+$; $\pi^0 \mu^+ \nu_\mu$ and

$K^0 \rightarrow \pi^+ \pi^-$; $\pi^0 \pi^0$; $\pi^+ \pi^- \pi^0$; $3\pi^0$ decays followed by the π^\pm and μ^\pm decays. The γ -rays are produced mainly by $\pi^0 \rightarrow 2\gamma$ decays. Well above the CR knee where $\beta_j \approx 3 - 1/3 - 0.06 \approx 2.61$, inside/near source hadronic meson production by cosmic rays yields

$$\Phi_\nu(E) \approx 0.52 \Phi_\gamma(E). \quad (4)$$

per ν flavor. Eqs. (3),(4), cannot be tested directly with current data because they neglect the attenuation of high energy γ -rays, and because the NBR was measured at $E_\nu > 30$ TeV, while the published Fermi-LAT data on the GBR (Ackermann et al. 2012) and on the extragalactic gamma background (Ackermann et al. 2015) are limited to $E < 1.2$ TeV (see Figs. 1,2) (Other recently reported measurements of the high energy GBR with Cherenkov telescopes such as those with H.E.S.S around 15 TeV (Abramowski et al. 2014) and in the ARGO-YBJ experiment around 1 TeV, (Ma 2011) were limited to the Galactic plane $|b| < 2^\circ$.)

The attenuation of Galactic γ -rays of energy below TeV is negligible, while the observed extragalactic γ -ray background (EGB) is strongly absorbed above 100 GeV. The full sky GBR measured with Fermi-LAT in the energy range 100 GeV - 2 TeV can be corrected for the attenuation of the EGB and used in Eq.(3) to predict Φ_ν in this energy range, and then it can be extrapolated to the energy range of the NBR detected with IceCube using $\phi_\nu(E) \propto \sigma_{\text{in}}((1+z) 20 \text{ E}) \Phi_s((1+z) 20 \text{ E})$, which follows from Eq. (1) for extragalactic CR sources. In this relation, $1+z \approx 2.5 \pm 0.5$ is the redshift at the peak of star formation rate (i.e., of supernova explosions and GRBs) and of the evolution function of the emission by BL Lac objects - presumably the main extragalactic sources of high energy CRs.

Eq. (1) predicts that the non attenuated EGB behaves like $E^{-2.31}$ well below the CR knee. Indeed, the EGB measured with Fermi-LAT below 820 GeV was best fit (Ackermann et al. 2015, Model C) with an exponential cutoff power-law,

$$\Phi_{\text{EGB}} \approx (6.42 \pm 0.40) \times 10^{-7} (E/\text{GeV})^{-2.30 \pm 0.02} e^{-E/E_c} \text{ fu} \quad (5)$$

where $E_c \approx 366 \pm 100$ GeV ($\chi^2/\text{df} = 6.9/23$). This best fit is shown in Fig. 1. Presumably, the power-law represents the unattenuated EGB at energies well below the "knee", produced by high energy cosmic rays in external galaxies. Eqs. (3) and (5) then yield $\phi_\nu \approx 1.03 \times 10^{-11}$ fu per ν flavor at $E=100$ GeV whose extrapolation to $E > 50$ TeV yields an isotropic extragalactic [EG] neutrino flux per ν flavor,

$$E^2 \Phi_\nu[\text{EG}] \approx (0.85 \pm .30) \times 10^{-8} \left[\frac{E}{100 \text{ TeV}} \right]^{-0.61 \pm .05} \text{ GeV}^2 \text{ fu}. \quad (6)$$

Similarly, the Galactic [MW] contribution $E^2 \Phi_\gamma[\text{MW}] = E^2 (\Phi_{\text{GBR}} - \Phi_{\text{EGB}}) \approx 2.49 \times 10^{-7} \text{ GeV}^2 \text{ fu}$ to the GBR at $E=\text{TeV}$ and Eq. (3) can be used to estimate $\Phi_\nu[\text{MW}]$, which can be extrapolated to $E > 50 \text{ TeV}$, yielding

$$E^2 \Phi_\nu[\text{MW}] \approx (2.62 \pm .20) \times 10^{-8} \left[\frac{E}{100 \text{ TeV}} \right]^{-0.61 \pm .05} \text{ GeV}^2 \text{ fu} \quad (7)$$

per ν flavor. The predicted energy flux of the NBR (all flavors) obtained from the ‘unattenuated GBR’,

$$E^2 \Phi_\nu \approx (1.04 \pm 0.15) \times 10^{-7} \left[\frac{E}{100 \text{ TeV}} \right]^{-0.61 \pm .05} \text{ GeV}^2 \text{ fu}, \quad (8)$$

is compared in Fig. 2 to the all-flavors NBR measured with IceCube (Aartsen et al. 2015). The separate contributions of the Milky Way ($\approx 76\%$) and extragalactic sources ($\approx 24\%$) to the NBR are shown in Fig. 3. Assuming the all flavors NBR flux to be isotropic, its best fit single power-law between 25 TeV and 2.8 PeV by the IceCube collaboration (Aartsen et al. 2015), $E^2 \Phi_{\text{NBR}} \approx (6.69 \pm 1.20) \times 10^{-8} (E/100 \text{ TeV})^{-0.50 \pm .09} \text{ GeV}^2 \text{ fu}$ is in rough agreement with Eq. (8).

The sky distribution of the NBR measured with IceCube is expected to coincide with that of the unattenuated high energy GBR, which is roughly that measured by Fermi-LAT at 100 GeV. This distribution that is peaked sharply around the Galactic center is shown in Fig. 4. Its peak, however, subtends only a small solid angle: The GBR that was measured with Fermi-LAT near 100 GeV (Ackermann et al. 2012) suggests that only $\sim 4.2\%$ of the neutrino events point back towards the Galactic center within latitudes $-8^\circ \leq b \leq +8^\circ$ and longitudes $-80^\circ \leq l \leq +80^\circ$, which cover only $\approx 0.43\%$ of the full sky. Also plotted are the sky distribution of the GBR at $E > 1 \text{ GeV}$ measured with EGRET aboard the Compton Gamma Ray Observatory and normalized to the flux measured by Fermi-Lat at 100 GeV. The diffuse gamma-ray emission (flux and sky distribution) from the Galactic plane ($0^\circ < b < 2^\circ$) and from point sources measured at higher energies (e.g., Abramowski et al. 2014 and references therein) with buried muon detectors (e.g., CASA-MIA), water Cherenkov detectors (e.g., Milagro and HWAC) and atmospheric Cherenkov detectors (e.g., H.E.S.S., MAGIC, and VERITAS), are generally consistent within errors with that extrapolated from the Fermi-LAT GBR assuming $\Phi_\gamma(E) \propto E^{-2.30}$ modified by attenuation in the Galactic and extragalactic background light.

4. Cosmic ray positrons near Earth

A detailed derivation of the expected flux of high energy cosmic ray positrons near Earth produced in hadronic interactions of cosmic ray nucleons in the local ISM, and its

comparison to the flux measured with high precision by the AMS02 collaboration (Aguilar et al. 2015) is presented in Dado & Dar 2015. Here we summarize it for completeness.

In a steady state, the local flux $\Phi_{e^+}(E)$ of e^+ 's produced in the ISM satisfies

$$\frac{d}{dE}[b(E) \Phi_{e^+}(E)] = J_{e^+}(E) \quad (9)$$

where $b(E) = -dE/dt$ is the loss rate of e^+ energy by radiation (rad) and by escape (esc) from the Galaxy by diffusion through its turbulent magnetic fields, and

$$J_{e^+}(E) \approx K_{e^+} \sigma_{\text{in}}(\text{pp}) n_{\text{ism}} c \Phi_p \quad (10)$$

is the local production rate of CR positrons in the ISM whose nucleon density in the solar neighborhood is n_{ism} . The solution of Eq. (9) is

$$\Phi_{e^+}(E) \approx K_{e^+} \sigma_{\text{in}}(\text{pp}) n_{\text{ism}} c \tau_e \Phi_p(E) / (\beta_j - 1). \quad (11)$$

where Φ_p is given by Eq. (2), $n_{\text{ism}} \approx 0.9 \text{ cm}^{-3}$ in the solar neighborhood (e.g. Kalberla & Dedes 2008), $K_{e^+} \approx 7 \times 10^{-3}$ for $\beta_j \approx 2.7 - 0.06 = 2.64$ and $\tau_e = E/(dE/dt)$ is the mean lifetime of positrons in the ISM due to their escape from the Galaxy by diffusion ($dE/dt \sim -E/\tau_{\text{esc}}$) and radiative energy losses (inverse Compton scattering of background photons and synchrotron radiation). It satisfies $1/\tau_e = 1/\tau_{\text{esc}} + 1/\tau_{\text{rad}}$, i.e., $\tau_e = \tau_{\text{esc}} \tau_{\text{rad}} / (\tau_{\text{esc}} + \tau_{\text{rad}})$.

For random Galactic magnetic fields with a Kolmogorov spectrum

$$\tau_{\text{esc}} \approx 7.5 \times 10^{14} (E/\text{GeV})^{-1/3} \text{ s} \quad (12)$$

where the normalization has been adjusted to the value obtained by Lipari (2014) from a leaky box model analysis of the flux ratio $^{10}\text{Be}/^9\text{Be}$ measured with the Cosmic Ray Isotope Spectrometer (CRIS) in the energy range 70-145 MeV/nucleon (Yanasak et al. 2001).

The radiative life time due to synchrotron emission in the local ISM magnetic field with energy density $U \approx B^2/8\pi \approx 0.40 \text{ eV/cm}^3$ and inverse Compton scattering of the local radiation background (diffuse Galactic light (DGL) with energy density $U \approx 0.41 \text{ eV/cm}^3$, far infra red (FIR) light with $U \approx 0.40 \text{ eV/cm}^3$, and cosmic microwave background (CMB) with $U \approx 0.26 \text{ eV/cm}^3$), was calculated in the Thomson and Klein Nishina regimes following the approximations introduced by Schlickeiser & Ruppel (2010). Other energy loss mechanisms that are important only at energy well below 10 GeV (Coulomb scattering, ionization and bremsstrahlung) as well as threshold effects, geomagnetic shielding and solar modulation, were included for completeness through a best fit phenomenological depletion factor $D(E) = 1 - \exp(-(E/V)^\alpha)$, which depends on the time of the measurements but does not affect the behavior at $E > 10 \text{ GeV}$.

In Fig. 5, the flux measured with AMS02 (Aguilar et al. 2015) is compared to the expected local flux of CR e^+ 's as given by Eq.(11) where $K_{e^+} \Phi_p(E) \propto E^{-\beta}$ has been replaced by $\Phi_p(E/\bar{x}_{e^+})/\bar{x}_{e^+}$ with the CR proton flux measured with AMS02 (Aguilar et al. 2015). As can be seen from Fig. 4, the agreement is quite good.

5. Conclusions

We have shown that the observed fluxes of very high energy backgrounds of astronomical neutrinos (NBR) and gamma rays (GBR), measured respectively with IceCube and Fermi-LAT, satisfy a simple relation, which follows from a common production in high energy hadronic collisions of cosmic rays in/near their main Galactic and extragalactic sources. An additional stringent test of the common hadronic origin of the high energy NBR and GBR is whether the sky distribution of the NBR measured with IceCube is approximately that of the unattenuated GBR near 100 GeV. Such a test, however, requires much higher statistics than currently available from IceCube. We have also shown that the observed flux of high energy cosmic ray positrons near Earth measured with AMS02 is in good agreement with that expected from hadronic cosmic ray production in the local ISM. Hence, we conclude that *at present* the observed fluxes, spectra, and sky distributions of the high energy astronomical neutrinos, gamma rays and cosmic ray positrons do not provide any compelling evidence for decay/annihilation of dark matter particles.

Appendix A: Photo-pion origin of the NBR and GBR?

A.1: Upper bound on the NBR ?

A "model-independent upper bound"

$$E_\nu^2 \Phi_\nu < 2 \times 10^{-8} \text{ GeV}^2 \text{ fu} \quad (13)$$

(per neutrino flavor) for the energy flux of extragalactic NBR above 100 TeV was derived by Waxman & Bahcall (1999). It was based on the assumption that the NBR is produced by the extragalactic cosmic ray protons in proton-photon collisions in CR sources which are optically thin. This "model independent upper bound", however is a model dependent estimate fraught with incorrect extrapolation (see, e.g., Ahlers, et al. 2005) and incomplete consequences of arbitrary choices. When properly corrected, this "upper bound" increases nearly by *two orders of magnitude!* and becomes practically useless.

Waxman & Bahcall (1999) assumed that the flux of ultra high energy (UHE) cosmic

rays above the CR ankle observed at Earth is a universal flux of extragalactic CR protons with an energy independent injection-rate per comoving volume (Waxman 1995),

$$E_{\text{CR}}^2 \frac{d\dot{N}_{\text{CR}}}{E_{\text{CR}}} \approx 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}. \quad (14)$$

Assuming that this injection rate is valid all the way down to 100 TeV, and that each cosmic ray proton photo-produces at most a single π^+ before escaping the source, Waxman & Bahcall (1999) obtained a "model-independent upper bound"

$$E_\nu^2 \Phi_\nu < 2 \times 10^{-8} \text{ GeV}^2 \text{ fu} \quad (15)$$

(per neutrino flavor) for the energy flux of the extragalactic NBR in the energy range 100 TeV to 100 PeV. If the UHE cosmic rays that are observed on Earth are extragalactic in origin, they must be protons. This is because of the rather short lifetime of extragalactic UHE CR nuclei due to their photo-disintegration in collisions with the extragalactic background light (Stecker 1969). A proton-dominated composition is also indicated by the observed break near $(5 \pm 1) \times 10^{19}$ eV in the spectrum of the UHE cosmic rays observed with the Hires (Abbasi et al. 2008), Pierre Auger (e.g., Abraham et al. 2010), and the Telescope Array observatories, that coincides with that predicted by Greisen (1966), and Zatsepin & Kuzmin (1966) for UHE extragalactic CR protons. However, Waxman & Bahcall (1999) also assumed a spectrum $dN_{\text{CR}}/dE \propto E^{-2}$ of the UHE extragalactic CR protons, which extends all the way down to PeV energies, while the observed flux of the UHE CRs below the GZK cutoff is well represented by (Aab et al. 2015) $\Phi_p \approx 0.2 (E/\text{GeV})^{-2.71} \text{ fu}$. This spectral behavior of UHE CR protons also well represents, within errors, the measured spectrum of CR protons below the all particle CR ankle (Apel et al. 2013) down to ~ 100 PeV, presumably the CR proton ankle (below the proton ankle, diffusion in the Galactic turbulent magnetic fields with a Kolmogorov spectrum changes their spectral index to $\approx -2.71 - 1/3 \approx -3.04$). In a steady state, the extragalactic CR spectrum is identical to the CR source spectrum. The observed extragalactic flux of CR protons with a power-law index -2.71 (Aab et al. 2015) extrapolated down to 100 TeV yields an energy flux $\approx 3.5 \times 10^3$ times larger than that of an extragalactic flux of CR protons with power-law index -2 postulated by Waxman & Bahcall (1999).

If the production of high energy neutrinos above 100 TeV is dominated by the decay of π^+ from $p\gamma \rightarrow \Delta^+(1232) \rightarrow n\pi^+$, then the π^+ 's carries on average a fraction $E'_\pi/M_{\Delta^+} \approx 0.22$ of the energy of the incident protons where E'_π is the π energy in the Δ^+ rest frame. Each neutrino from the π^+ decay carries an average energy $\langle E_\nu \rangle \approx E_\pi/4$. Hence, production of neutrinos through photo-production of $\Delta^+(1232)$'s by high energy cosmic ray protons in *optically thin sources* satisfies

$$\Phi_\nu \approx (1/2) (0.22/4)^{1.71} N_\Delta \Phi_p \approx 3.5 \times 10^3 N_\Delta \Phi_p \quad (16)$$

per neutrino flavor (assuming complete flavor mixing by neutrino oscillations), where $N_\Delta = \sigma_{p\gamma} N_\gamma \ll 1$ is the mean number of Δ^+ 's produced in collisions of a single UHE CR proton with a photon column density N_γ before it escapes into the intergalactic space. Since the power-law fluxes of CRs and neutrinos from the CR sources have the same power-law index, they suffer the same redshift. Hence, for a constant N_Δ per CR proton, all the dependence of Eq. (16) on cosmic evolution is through the dependence of the accumulated Φ_p on cosmic evolution.

But, a high energy CR proton loses $\sim 22\%$ of its energy in the reaction $p\gamma \rightarrow \Delta^+(1232) \rightarrow n\pi^+$ followed by $n \rightarrow p e^- \bar{\nu}_e$. Since the branching ratio for π^+ production is $\approx 1/2$, in order to photo produce a single π^+ , each UHE proton must produce on average two Δ^+ 's. Hence, such protons emerge from their sources with a fraction $\approx (0.78)^2 \approx 0.61$, of their initial energy. For a spectral index -2.71, it implies that the in-source flux of such CR protons must be larger by a factor $\approx (1/0.61)^{1.7} \approx 2.34$ than that of the emergent flux in order to produce a single π^+ per observed CR proton. Such a flux produces a neutrino flux larger by a factor 2.34 than the observed flux of UHE CR protons. Consequently, the maximal neutrino flux from "thin sources", which were defined by Waxman & Bahcall (1999) as sources producing a single π^+ per CR proton, the energy flux per neutrino flavor produced in-source is

$$E^2 \Phi_\nu \approx 4.7 \langle x_\nu \rangle^{1.71} E^2 \Phi_p(E) \approx 10^{-6} \left[\frac{E}{100 \text{ TeV}} \right]^{-0.71} \text{ GeV}^2 \text{ fu.} \quad (17)$$

This estimate for "maximally thin" sources is larger by nearly *two orders of magnitude* than the Waxman-Bahcall "upper bound", which was based on an assumed power-law index -2 of the extragalactic CR protons above the CR ankle instead of the observed -2.71 (e.g., Aab et al. 2015 and references therein) and was used for extrapolating the energy flux of the extragalactic UHE CR protons down to 100 TeV, and which neglected the energy loss of CR protons in source in producing "at least a single π^+ " (i.e., two Δ^+ 's) per CR proton.

A.2: Photo-pion origin of the NBR ?

If the production the NBR and GBR above 30 TeV is dominated by the decay of photo-pion produced in CR proton-photon collisions $p\gamma \rightarrow \Delta^+(1232) \rightarrow n\pi^+$, and $\rightarrow p\pi^0$, respectively, in/near source (Mannheim 1993), then, for CR protons with in-source spectral index $\beta_s = -2.7$, the unattenuated NBR and GBR satisfy the relation

$$\Phi_\nu \approx (1/2)(m_{\pi^+}/2m_{\pi^0})^{1.7} \Phi_\gamma \approx 0.16\Phi_\gamma. \quad (18)$$

per ν flavor. However, if the steepening of the CR spectrum at the CR knee is due to a transition from Kolmogorov diffusion to drift motion, while the spectral index of the source

spectrum $\beta_s = -2.3$ does not change (Anchordoqui et al. 2014b), then $\Phi_\nu \approx 0.21\Phi_\gamma$ per ν flavor. Hence, the extragalactic NBR expected from the observed EGB with Fermi-LAT,

$$E^2 \Phi_\nu[\text{EG}] \approx (1.8 \pm .30) \times 10^{-9} \left[\frac{E}{100 \text{ TeV}} \right]^{-0.61 \pm .05} \text{ GeV}^2 \text{ fu}, \quad (19)$$

i.e., much smaller than that measured with IceCube.

The Galactic contribution of photo-pion production by CR interactions in/near source to the NBR below ~ 3 PeV is strongly suppressed by a too high effective energy threshold. The effective threshold energy for photo-pion production in collisions of CRs with the typical gray body radiation field of a mean photon energy ϵ_γ is

$$E_{\text{th}} \approx \frac{m_\pi m_p}{2 \epsilon_\gamma} \approx \frac{6.5 \times 10^{16}}{\epsilon_\gamma/\text{eV}} \text{ eV}. \quad (20)$$

The mean photon energy of stellar light in the ISM and IGM is $\epsilon_\gamma \sim 1 \text{ eV}$. Hence, the minimal energy of the bulk of neutrinos from Galactic photo-pion production is smaller by a factor ≈ 20 , yielding an energy threshold $E_\nu > 3 \text{ PeV}$ for Galactic photo-pion neutrinos produced by Galactic cosmic rays in/near source and in the ISM.

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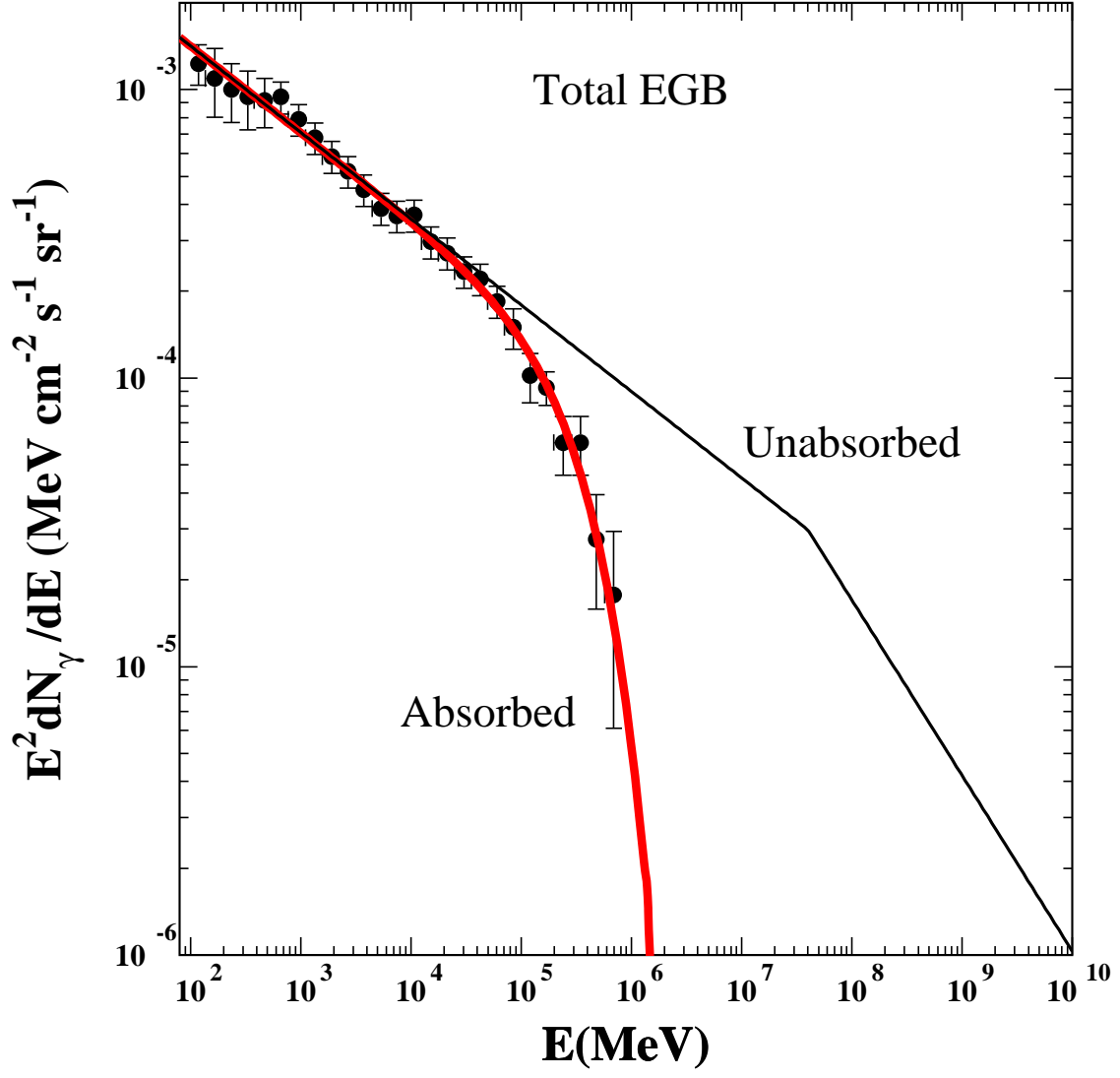


Fig. 1.— The flux of the extragalactic gamma-ray background (EGB) as function of gamma-ray energy measured with Fermi-LAT (Ackermann et al. 2015) and the best fit exponentially cutoff power-law. The straight line represents the unabsorbed power-law EGB.

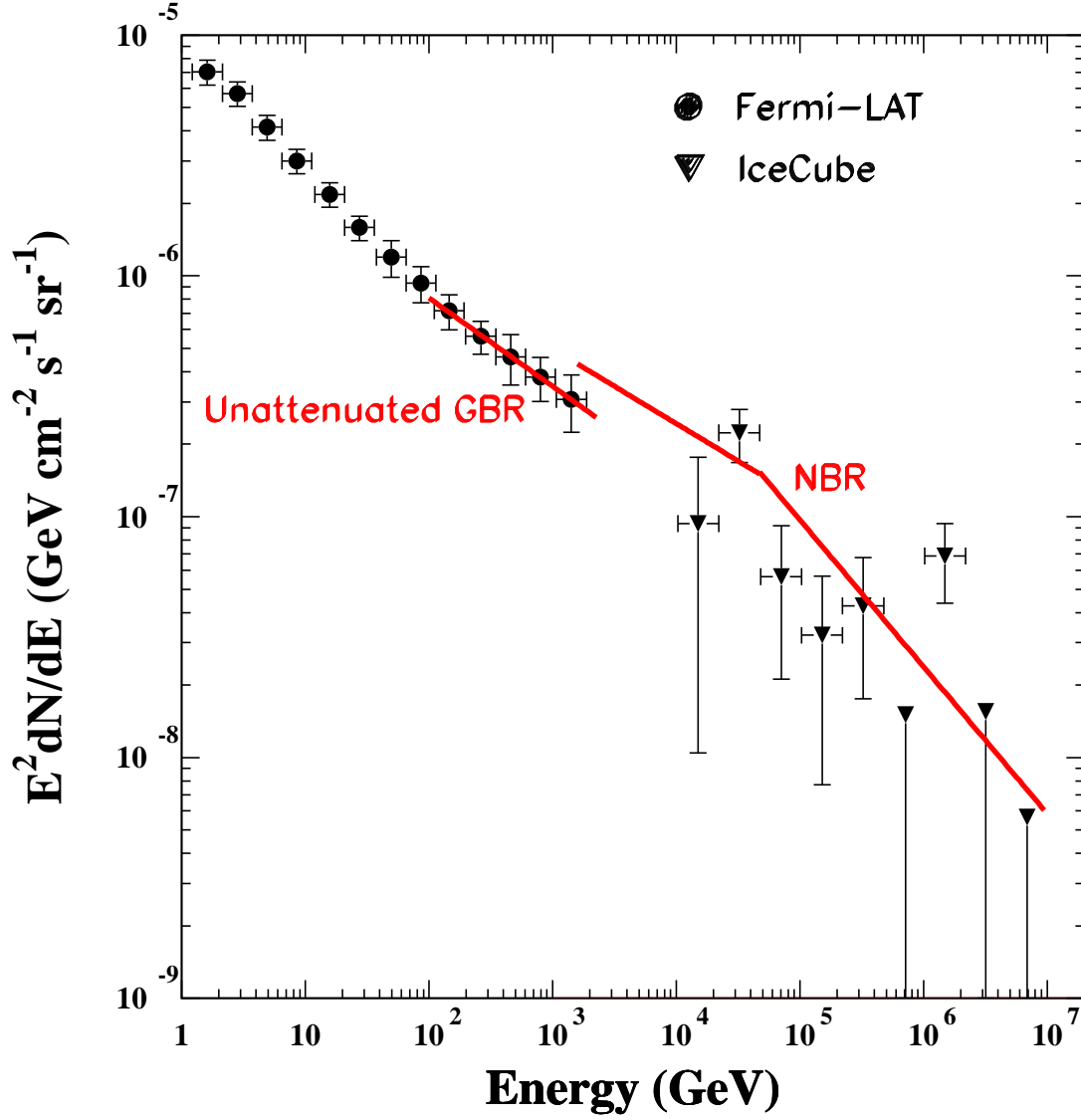


Fig. 2.— Comparison between the energy flux of the NBR (all flavors) above 20 TeV measured with IceCube (Aartsen et al. 2015) and that expected from the unattenuated GBR below 2 TeV as inferred from the GBR and EGB measured with Fermi-LAT (Ackermann et al. 2012,2015). Also shown is the best fit single power-law to the unattenuated GBR (spectral index -2.36) in the energy range 100 GeV - 2 TeV estimated from the Fermi-LAT measurements.

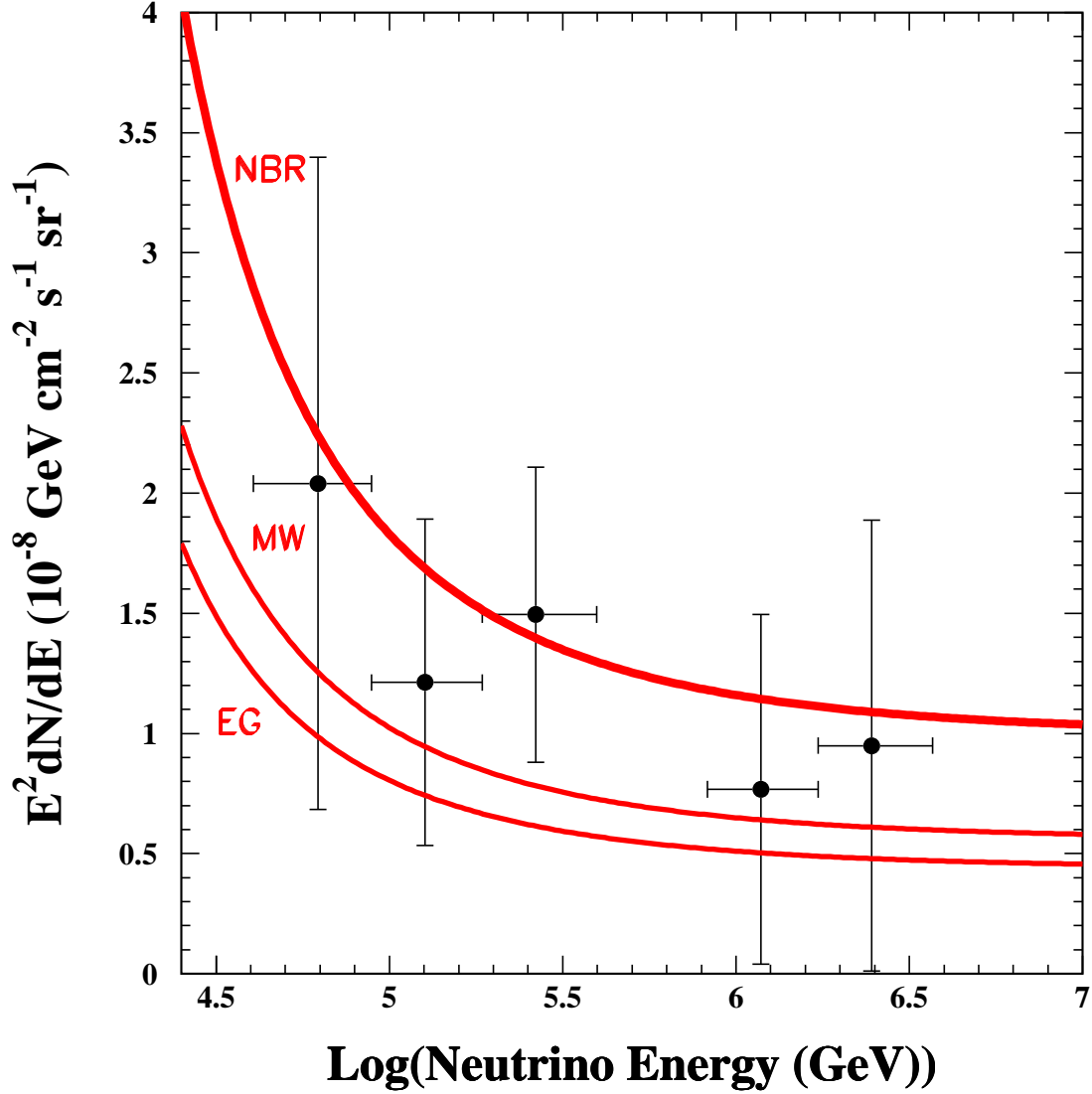


Fig. 3.— Comparison between the energy flux of the NBR (per ν flavor) above 50 TeV, which was inferred from the first 3 years measurements with IceCube (Aartsen et al. 2014), and the flux of the NBR (per ν flavor) expected from the GBR and EGB, which were measured with Fermi-LAT (Ackermann et al. 2012,2015). The separate contributions of extragalactic (EG) neutrinos and neutrinos from our Galaxy (MW) to the NBR are also shown.

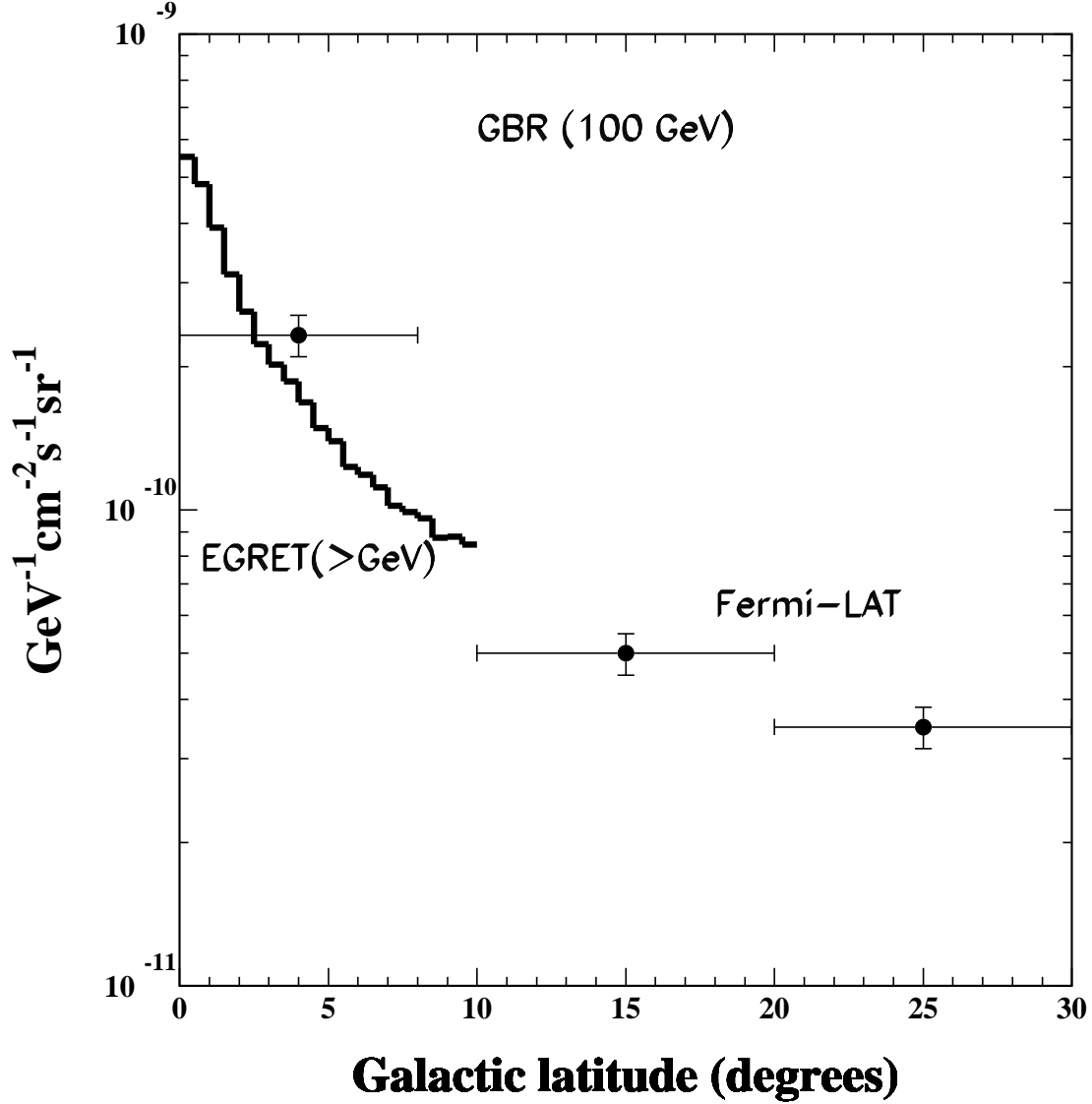


Fig. 4.— The sky distribution of the high energy GBR as function of Galactic latitude, observed with Fermi-LAT (Ackermann 2012) at 100 GeV. Also shown is the sky distribution observed with EGRET aboard the Compton Gamma Ray Observatory at $E > 1$ GeV (Pohl et al. 1997) normalized to the Fermi-LAT distribution. The NBR is predicted to have nearly the same sky distribution as that of the unattenuated high energy GBR.

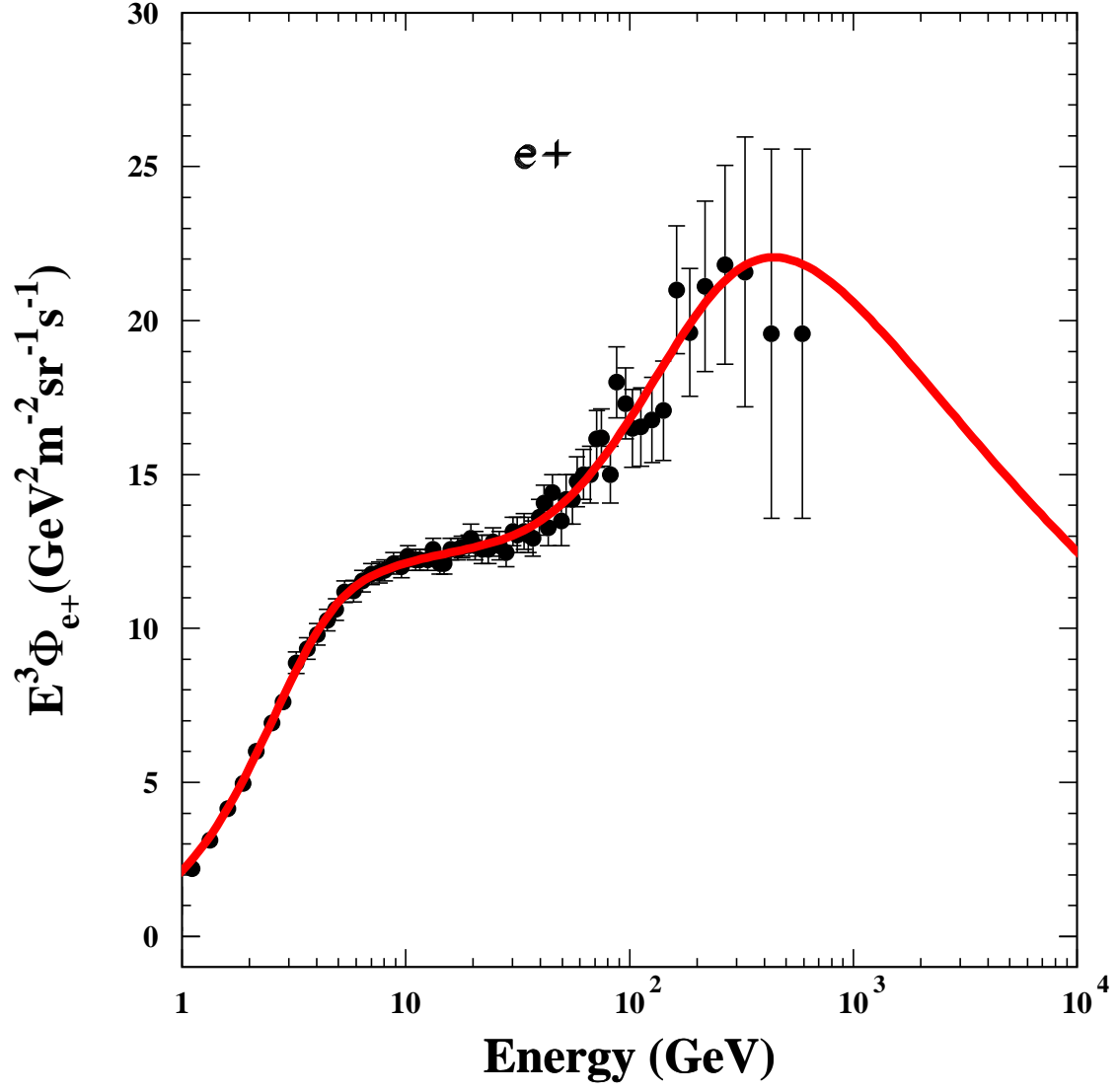


Fig. 5.— Comparison between the CR positron flux measured with AMS02 (Aguilar et al. 2014) and the flux expected from positron production in the local ISM.